SPECIAL ARTICLE

Electrocardiogram of the Humpback Whale (*Megaptera novaeangliae*), With Specific Reference to Atrioventricular Transmission and Ventricular Excitation

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Objectives. **The objective of the study was to record the electrocardiogram (ECG) of a large whale to obtain crucial data for comparative electrophysiologic analysis.**

Background. **The data were needed to establish the mismatch between heart size and PR interval and QRS duration in mammals.**

Methods. **In the waters off the coast of Newfoundland, in two humpback whales (*Megaptera novaeangliae*) with an estimated weight of 30,000 kg a 1-lead ECG was recorded, enabling reliable assessment of P waves and QRS complexes.**

Results. **It was found that both the PR interval (atrioventricular [AV] transmission time) and QRS duration (ventricular excitation) are extremely short for animals of this size. These findings are difficult, if not impossible, to explain on the basis of currently accepted electrophysiologic theories. However, the narrow QRS complex may be due to a very dense His-Purkinje network in the ventricular wall of whales. Alternative mechanisms that can explain the function of the mammalian AV node need to be considered and explored.**

Conclusions. **The results of the study may be of value for the understanding of the ECG in humans.**

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"The relationship of heart size to heart rate and to the time intervals of the electrocardiogram, in particular to the P-R interval and the QRS duration, plays an important role in the interpretation of normal and abnormal human tracings."

This is the opening sentence of a 1953 study by King, Jenks and White (1), entitled "The electrocardiogram of a Beluga whale." However, the crucial data referred to in that statement were not available until recently.

In 1913, Waller (2) was the first to draw attention to the correlation between the size of an animal and the duration of the atrioventricular (AV) transmission time (PR interval) on the electrocardiogram (ECG). In 1927, Clark (3) wrote: "The most striking thing is that the PR interval varies so little in different animals." Further studies of AV transmission times in different mammalian species have demonstrated a so-called mismatch between heart weight (4–7), which is closely related (0.6%) to body weight (8,9), and increments in the AV interval. For example, the PR interval in an elephant is only 10 times longer than that in a rat, whereas the heart of an elephant weighs 25,000 times as much as a rat heart.

To more fully characterize the relations between AV transmission time and heart weight and size (roughly proportional to the third root of heart weight), it would be important to know the PR interval in mammals considerably larger than elephants. Earlier attempts to record an ECG of sufficient quality to measure the PR interval and QRS duration in large whales, especially the gray whale (*Eschrichtius robustus*), in their natural habitat were unsuccessful (10–12). Therefore, we attempted to record the ECG in humpback whales (*Megaptera novaeangliae*) (Fig. 1). During the summer, marine mammals often are entrapped in the large nets used for fishing off the coast of Newfoundland (13a). Among them are humpback whales, a circumstance that makes it possible to approach these whales and observe them at close range.

Methods

Experimental site and subjects. In June 1991, two of the authors (K.B., V.B.) went to St. John's, Newfoundland and,

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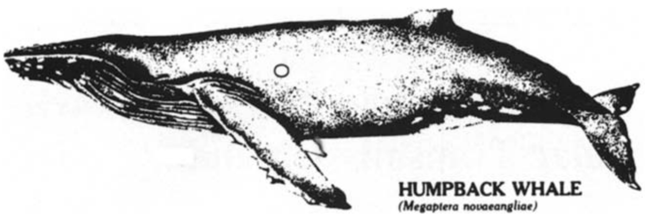


Figure 1. Artist Robin Makowski's impression of the humpback whale. The **circle** close to the pectoral fin represents the location of the suction electrode. Reprinted with permission from the American Cetacean Society.

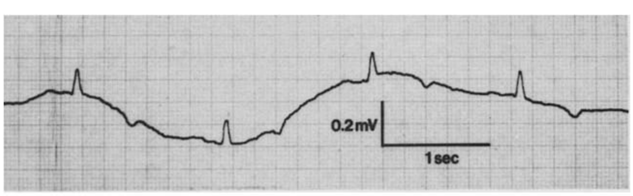
with the help of the local environmentalist, Dr. Jon Lien, succeeded in recording a 1-lead ECG in two humpback whales, each with an estimated length of 30 feet (10 m). The recordings were of sufficient duration and quality to enable reliable assessment of P waves and QRS complexes; they were also adequate for measuring the PR interval and QRS duration (Fig. 2).

While the whales were entrapped in the fishermen's nets and under observation, they could not swim far but were free to dive to about 5 m. They did not seem to be frightened, had no visible injuries and were easy to work with. After the study, all whales were released from the nets and some actually had to be encouraged to leave the site. They were in apparent good health at the time of their departure. During the 2-week period in the Newfoundland area, eight humpback whales were approached, but good quality ECG recordings could be obtained from only two.

Electrocardiographic recordings. To obtain the recordings, a 10-cm diameter suction electrode was placed just behind the left pectoral fin and served as a unipolar lead. The optimal location for the placement of the suction cup electrode on the humpback whale was selected by determining from autopsy the position of the heart in the thorax of one whale found dead in the area. The indifferent electrode was placed in (sea) water. Through long coaxial cables, the electrodes were connected to a portable ECG recorder and a Holter monitor. In both whales from which adequate recordings were possible, about 20 min of recording was obtained. The signals on the Holter tape were transferred to TEAC-R-71 format.

Data analysis. Because of noise and artifact interference on the tapes, it was difficult to identify individual P-QRST sequences and, therefore, to determine the PR interval for

Figure 2. Electrocardiographic strip from one of the two whales with recordings of good quality. Paper speed is 25 mm/s.



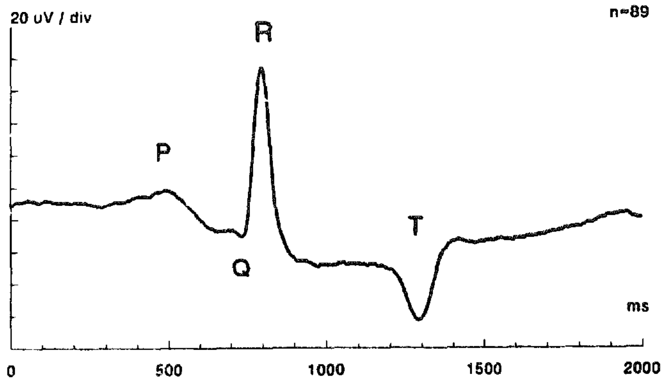


Figure 3. Averaged ECG from the second whale with recordings of good quality. Time (in ms) is shown on the X axis and voltage (in μV) on the Y axis. The low voltage is due to the short-circuiting effect of sea water. The PR interval (atrioventricular transmission time) is 400 ms; the QRS duration (ventricular excitation) is between 150 and 200 ms and the QT interval between 650 and 700 ms. The S wave is not visible in this lead.

single beats. Signal-averaging techniques were required. The recordings were analyzed by means of 250-Hz analog to digital conversion and the software program (Asystant) on a personal computer.

The RR interval histograms, and thus average heart rate, were obtained by measuring only those RR intervals between two clearly identified QRST complexes that were relatively free from artifact so that the presence of more complexes within the intervals could be excluded. Therefore, the actual number of QRS-T complexes on the tapes was greater than the number of RR intervals used for the histograms.

From P-QRST complexes previously obtained from killer whales (*Orcinus orca*) in sea aquaria in Vancouver, Canada, Mexico City, Mexico and Orlando, Florida, we had learned that the average amplitude of the P wave in these mammals is approximately 10% of that of the R wave. Estimating that approximately 100 complexes/whale would be available for the averaging process, resulting in an expected 10-fold reduction in noise level, only those complexes surrounded by artifact and noise with an amplitude <50% of the R wave amplitude were used for averaging. These P-QRST complexes were selected by visual inspection. In the averaging process, R waves served as the central reference. This procedure resulted in one average P-QRST complex from which the variables could be measured in each whale (Fig. 3).

From the estimated length of both whales (approximately 10 m each), their weight could be estimated (13b). According to Slijper (14), for the humpback whale it is justified to apply the rule of thumb of approximately 1 ton/foot. However, according to Evans (13b), the actual ratio may be closer to 1.5 tons/foot bringing the whale's body weight, at a conservative approximation, to 30,000 kg and its heart weight to 150 to 180 kg. The size of the whale heart, and thus the length of the His-Purkinje system, is approximated as the third root of

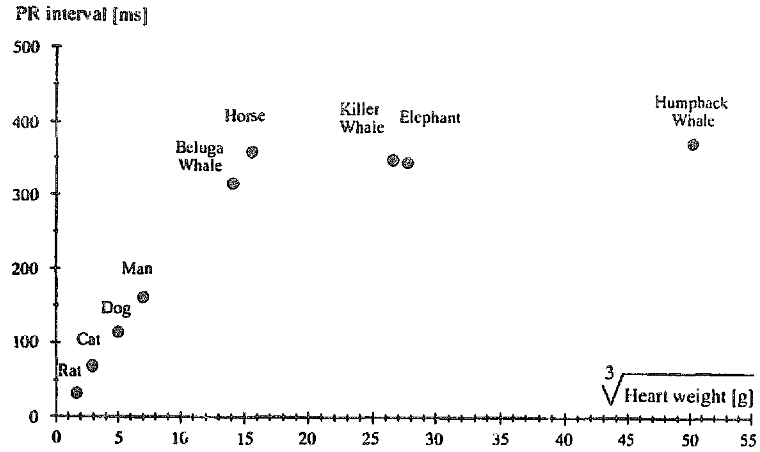


Figure 4. Relation between the PR interval (in ms) and heart size (in cm) presented as the third root of heart weight (in g). For details, see text.

its weight, being on the order of 55 cm; however, because the heart is not a cube, the actual length of the conduction system is almost certainly greater.

Results

The histogram data revealed that the averaged heart rate in both whales was on the order of 30 to 35 beats/min. The averaged P-QRST complex from 89 complexes in one of the humpback whales is shown in Figure 3. This P-QRST complex is almost identical to the one in the second whale. From the averaged P-QRST complex data, we can conclude that the PR interval and QRS duration in humpback whales of this size do not exceed 400 and 200 ms, respectively.

Discussion

This is the first time that a credible ECG with clearly visible P waves and QRS complexes has been recorded in a mammal of this size. The heart weight equals the body weight of two adult men and is more than 6 times the weight of an elephant heart and 20 to 30 times the weight of a horse heart. The results are revealing because these observations demonstrate that in the hearts of these two whales, the PR interval and QRS duration are of the same order of magnitude as those in much smaller mammals such as horses and cattle (15). Kawamura (16) studied the length of the AV node in mammalian hearts of different sizes and found an almost linear relation between length and size. These data imply that the AV node in the humpback whales we studied must have been considerably longer and larger than that of a horse or cow, for example. The data confirm those of Clark (3) and our own hypotheses (6) regarding the apparent mismatch between AV transmission times and heart size in many species.

Accuracy of the measurements. Possible physiologic and methodologic considerations that might affect our results need to be addressed.

First, these whales were entrapped in nets for several days, possibly representing a nonphysiologic state with consequent alterations in heart rate and conduction characteristics. However, the experienced marine biologist present during the recordings did not feel that the whales showed signs of distress. Similar conclusions were drawn from watching the whales' behavior on videotapes of the ECG recording periods.

Second, the interpretation of averaged complexes may introduce some nonphysiologic variance. For instance, the RR intervals, as shown by the histogram, were not constant and, therefore, the PR intervals can be expected to vary as well. The PR intervals were measured from the onset of the P wave to the onset of the R wave. Averaging many complexes with varying PR intervals while keeping the R wave in a stable central position will lead to a broader P wave, rendering the onset of the P wave on the averaged ECG difficult to determine with certainty. Potentially, the PR interval measured in this manner will be close to its maximal value.

In any case, we should be cautious about the accuracy of the measurements because it is difficult to determine with certainty where the P wave begins and the QRS complex ends. Moreover, there could be isoelectric periods in the 1-lead ECG due to lead projection or a certain degree of cancellation, or both (17).

Comparative AV transmission times. To place the AV transmission data in perspective, Figure 4 shows the PR interval versus heart size in a selection of mammalian species (16). It can be seen that the PR interval does not increase significantly as the mammals get larger. There appears to be a leveling of the delaying function of the AV conduction system. On the basis of classic conduction concepts (18–20) and the similarity in morphologic appearance (21–23) of the AV conduction systems in various mammalian species, it is difficult to explain why in very large hearts with a large AV node and a long His-Purkinje system such as these whales must have (16,21), AV transmission (and His-Purkinje) times are not proportionately longer than those in smaller hearts. At the same time, although the AV

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August 1992:475–9

node contribution to AV transmission time seems to diminish as hearts get bigger, the protective function of the AV node against a rapid ventricular response to atrial tachycardia, flutter and fibrillation should be maintained (24). Thus, after a certain body mass is reached, AV transmission time is no longer a scaled physiologic variable; that is, it does not vary systematically with body size (25). If there were no discontinuity in AV junctional function as expressed in Figure 4, the PR interval in large whales would easily exceed 1 to 1.5 s. This increased value would almost certainly result in unwanted hemodynamic consequences (26). In other words, in large hearts, a proportionate increase in the PR interval would not further enhance the contribution of atrial systole to ventricular filling. Thus, in large mammals, the main task of the AV node, in addition to protective function against atrial arrhythmias, seems to be the fine tuning of AV delay to create an optimal efficacy of the circulation under varying physiologic conditions.

Possible explanations for the observations presented here, and previous data demonstrating the constancy of AV transmission times in species of widely differing size, include the concept that the AV node does not "conduct" in the classic sense (27). Alternative electrophysiologic mechanisms may be involved (28–30) or conduction velocity must increase markedly by as yet unexplained mechanisms without affecting the protective function of the AV junction.

Ventricular excitation. The narrow QRS complexes in hearts as large as these whale hearts seem to point to an otherwise unlikely high conduction velocity in the His-Purkinje system (20). This could at least in part also contribute to the short PR interval. However, whales probably have a very dense Purkinje network (21), as found in hoofed animals by Meyling and Ter Borg (31), an observation that may explain the limited QRS duration as a separate mechanism from the short PR interval.

Atrioventricular node function. We present these data as a hitherto missing piece in the knowledge of comparative AV node function in mammals. In 1927, Clark (3) came to the conclusion that "The delay at the a.-v. junction therefore varies relatively little in different species of Mammals." We may add to this that an increase in AV node area is almost certainly not accompanied by an increased transmission time through this structure, the mechanisms for which are as yet unclear.

The intriguing phenomena of a short PR interval and QRS duration in large mammals deserve further study and eventually an electrophysiologic, morphologic and biochemical explanation because, indeed, the rules governing the electrophysiologic functioning of the human heart should be applicable in the interpretation of comparative ECG findings and vice versa (1). At present, this does not seem to be the case.

Conclusions. The PR interval (AV transmission time) and QRS duration (ventricular excitation) in a humpback whale are extremely short in relation to its cardiac dimensions and the estimated length of the AV and His-Purkinje system. This finding cannot be satisfactorily explained on the basis of currently accepted electrophysiologic conduction theories. Alternative electrophysiologic and other mechanisms should be explored. Moreover, insight into AV node function is vital to our understanding of ventricular rate and rhythm in supraventricular arrhythmias such as atrial fibrillation (32).

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